

Investigating Effects of “Well Clear” Definitions on UAS Sense-And-Avoid Operations

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Unmanned aircraft systems (UAS) will be required to equip with sense-and-avoid (SAA) systems in order to fulfill the regulatory requirement to remain “well clear” of other air traffic. This study investigates the effects that different well-clear metrics have on the rate of well-clear violations and evaluates the distribution of distances between aircraft at a well-clear violation in high-altitude enroute airspace. The first analysis determines the predicted rate at which violations of well clear would occur between UAS and manned aircraft operating under instrument flight rules, indicating the frequency with which a sense-and-avoid system would create a nuisance alert. This analysis is done both with and without an algorithmic model of air traffic control (ATC) separation provision services. The second analysis determines the relationship between time-based well-clear metrics and the range at which the violation would occur, a relationship that may inform the required SAA surveillance range and the frequency with which violations would occur despite ATC separation standards still being maintained. The analyses are carried out using a fast-time simulation capability of the entire US air traffic system over a single day, including 3000 UAS and more than 50,000 manned aircraft. Results indicate that, without any separation provision, a UAS would encounter a manned aircraft with a range tau (defined as the ratio of the relative range to range rate) of 60 seconds only every six hours. Approximately 75% of such encounters would occur outside the ATC separation standard of 5 nmi.

I. Introduction

A “sense-and-avoid” (SAA) system on a unmanned aircraft system (UAS) will replace the “see-and-avoid” function provided by pilots in manned aircraft, which is an important contributor to today’s safe air traffic operations.¹ An SAA system must provide two services: self separation (SS), which keeps the aircraft “well clear” of other airborne traffic; and collision avoidance (CA), which avoids near-midair collisions (NMAC) with other aircraft using tactical and relatively short time-horizon maneuvers.¹ There are currently no accepted time- or distance-based standards for what it means for two aircraft to be “well clear,” that determination is left to the pilot’s discretion. In addition to the lack of an onboard pilot, another major difference between unmanned aircraft and manned aircraft from an air traffic control (ATC) standpoint stems from the various mission profiles of unmanned aircraft. Currently, almost all manned aircraft in high-altitude enroute and transition airspace fly from origin to destination along fixed airways, while many unmanned aircraft need to perform “mission-oriented” operations (e.g. a loitering pattern, grid pattern, or non-predetermined missions with frequently changing flight plans). This difference in mission profiles further complicates ATC separation provision services and procedures that are designed for manned aircraft since those non point-to-point operations of UAS in controlled airspace may create different conflict situations (i.e. encounter geometries) between unmanned and manned aircraft.² Existing aircraft encounter models do not incorporate these new UAS aircraft performance and mission characteristics.³ Therefore, to evaluate aircraft encounter characteristics for anticipated enroute and transition operations that include UAS, it is necessary to model UAS performing different mission profiles with aerodynamic characteristics typical of these aircraft in national airspace system (NAS)-based simulations.

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Since all aircraft in enroute and transition airspace are flying under Instrument Flight Rules (IFR) and are receiving ATC separation provision services (SPS), UAS should not, under normal operations, be required to initiate a self-separation maneuver to remain well clear of other aircraft in this airspace. However, as specified by current regulations that apply to manned aircraft, UAS pilots may still request trajectory changes to remain well clear from other aircraft. Such requests do not require a legal loss of separation to have occurred, and only depend on the definition of well clear or the existence of pilot-identified situations such as severe weather encounters or emergencies. An SAA system that allows intruder detection at much larger ranges than a pilot's eyes, along with proposed options for new quantitative definitions of well clear,⁴ could create more predicted well-clear violations (WCV) once UAS are allowed to access controlled airspace relative to existing manned aircraft operations. An analytical WCV threshold has been proposed based on the unmitigated risk of collision after crossing of the separation boundary from a set of random encounters between VFR aircraft under 18,000 ft.⁵ In this approach, well clear is framed as a relative state between aircraft (defined as the ratio of the relative range to range rate) for which the risk of collision is acceptable. The relationship between this (and alternative) definition(s) of well clear and the number of additional predicted violations needs to be evaluated in airspace classes other than that used to create the set of random encounters. Furthermore, these evaluations need to consider missions and vehicle performance that is consistent with what is expected of future UAS operations.

The primary goal of this study is to investigate the effects that several metrics of well clear will have on WCV rates and operations in the NAS. The proposed metrics are taken from a recent FAA report, variations on methods used by TCAS II,⁶ and distance-based metrics in analogous to separation minima employed by the ATC SPS. The first analysis presented in this paper investigates the effects of the well-clear definition on the WCV rate. It presents this analysis both with and without an algorithmic model of ATC SPS. The second analysis explores the effects of the well-clear metrics on NAS operations in terms of potential deviations from ATC clearances; this analysis assumes a UAS would maneuver whenever a WCV is predicted. A unifying goal of these analyses is to understand the relationship between time- and distance-based criteria for evaluating whether a particular relative state should be considered a WCV.

II. Metrics for Well Clear

The FAA-sponsored Sense-and-Avoid Workshop¹ defines SAA as “the capability of a UAS to remain well clear from, and avoid collisions with, other airborne traffic. SAA provides the intended functions of self separation and collision avoidance compatible with expected behavior of aircraft operating in the NAS.” The self separation (SS) function of an SAA system is intended as a means of compliance with the regulatory requirements (14CFR Part 91, §91.111 and §91.113) to “see and avoid” and to remain “well clear” of other aircraft.

The concept of well clear has been proposed as an airborne separation standard to which an SAA system must adhere,⁵ and performing SS correctly means remaining well clear from other aircraft. The well clear definition is essentially a separation standard used by the SS function to determine what actions to take to remain an appropriate distance from other aircraft. The standard will require that a UAS be able to sense and avoid other aircraft in sufficient time to remain well clear from the intruder. At a minimum, it should avoid initiating a collision avoidance maneuver on either the UAS or the intruder. The time or distance thresholds defining a WCV could be unique for each intruder based on closure rate, performance characteristics, encounter geometry, and other variables. Therefore, it is necessary to define an explicit and quantitative definition of well clear so that the contribution of the SS function to the overall safety for a given airspace can be unambiguously determined.

The second SAA workshop⁴ defines “well clear” as the state of maintaining a safe distance from other aircraft that would not normally cause the initiation of a CA maneuver on either aircraft. The following SAA implementation principles could also be utilized to define the well-clear standard:⁷

- Separation should be large enough to avoid corrective maneuvers from intruders (e.g., resolution advisories for TCAS-equipped intruders), to minimize traffic alert issuances by controllers, and to avoid excessive concern for proximate see-and-avoid pilots;
- Deviations should be small enough to avoid disruptions to traffic flow and vary appropriately with encounter geometry and operational areas (e.g. terminal, transition, enroute).

Although these criteria are necessary for SAA interoperability with the NAS, they have yet to be quantified. This paper begins to address the quantification of these criteria by determining how frequently aircraft in high-altitude enroute and transition airspace encounter each other as a function of the WCV definition and what the resulting disruptions are to traffic flows. Four metrics are used to evaluate well clear in this study, and they are introduced presently.

A. Range Tau

The first metric used to evaluate well clear in this study is based on “range tau”, where the metric is calculated as the maximum between the range tau and vertical tau computations. Range tau is derived as the ratio of range between aircraft to their range rate and measured in seconds:

$$\tau_{range} = -\frac{r}{\dot{r}}, \quad (1)$$

whereas, the vertical tau is calculated as the ratio of the altitude separation to the vertical closure rate and measured in seconds:

$$\tau_{vert} = -\frac{\Delta h}{\dot{h}}. \quad (2)$$

Note that a tau value is positive when the UAS and the intruder converge and negative when they diverge. This metric of tau represents an approximation of the time to closest point of approach (CPA), but is exact only in the case of a direct collision course (CPA is zero). If the aircraft will merely pass near each other, then tau is only an approximation of time to CPA. In this case, tau will decrease to a minimum value shortly before actual CPA and then increase. Since the ratio of range and range rate will generally be lower with closer points of approach, this minimum value of tau approximates the severity of the encounter. This property of tau means that selection of a minimum tau value at which to alert for a WCV determines not only the *time* to react to the threat, but also the size of protected airspace within which a given threat encounter will cause an alert. When an intruder aircraft is predicted to create an encounter with a tau value below the minimum, the SAA system may trigger an alert to a pending WCV.

B. Modified Tau

A problem with this simple metric of range tau occurs for encounters where the rate of closure is very low, as described in the TCAS II Manual.⁶ For these encounters the calculated tau may be large while the physical separation may be quite small, far less than a mile. In such a critical situation, the calculated tau value no longer assures adequate separation because a sudden acceleration that increases the closure rate (e.g., a turn) would not give sufficient alerting time to avoid a WCV or even an NMAC. To provide protection in these types of encounters, a modified alerting threshold, often referred to as “modified tau,” is used by TCAS II.⁶ This second metric uses a new parameter, “distance modification” (DMOD) to provide a minimum range at which to alert regardless of the calculated value of range tau. Similar to the “range tau” calculation, the modified tau metric is derived as a maximum between a modified tau and vertical tau computation. Modified tau is computed as

$$\tau_{mod} = \begin{cases} \frac{(r^2 - DMOD^2)}{r\dot{r}} & \text{for } r \geq DMOD \\ 0 & \text{for } r < DMOD \end{cases}, \quad (3)$$

whereas the vertical tau is the same as equation 2. The particular value of DMOD that should be used in this type of WCV metric needs further study, however for the purposes of this study; a DMOD constant of 1.1 nmi is used. This parameter corresponds to the TCAS II DMOD for most of Class A airspace.

C. Modified Tau with Horizontal and Vertical Miss-Distance Filters

The previous two metrics of a WCV can be problematic when two fast aircraft encounter each other. For example, if two aircraft on opposite headings are each traveling 600 kts with tracks horizontally offset by 5.9 nmi (so CPA will be 5.9 nmi) the range tau will be 35 s, low enough to be considered time to execute a collision avoidance maneuver even though a controller would consider the aircraft adequately separated. TCAS II remedies this problem by employing a horizontal miss-distance filter to remove alerts for encounters that will pass a distance more than approximately DMOD (1.1 nmi) apart.⁷ A similar filter is provided for vertical miss distances greater than about 700 ft. The definition of well clear may need to incorporate similar filters to avoid “nuisance” alerts, so the third metric evaluated in this paper will not consider a WCV any encounter with CPA larger than the selected value of DMOD. This metric would be the most similar to that used by TCAS II.

D. Distance-Based Threshold

The fourth metric for determining a WCV would be defined entirely by distance, though that distance would likely be variable depending on airspace considerations (e.g. Class A vs. B, arrival vs. departure). This would make the WCV definition consistent with a controller’s distance-based legal separation requirement and the NMAC volume, conceptually simple, and perhaps take advantage of the more complete sensor information that may be available to an SAA system than that afforded to TCAS. The previously described threshold criteria were designed to work with a surveillance sensor (a Mode-C or Mode-S transponder) that had accurate estimates of range, range rate, altitude, and altitude rate but a poor estimate of intruder bearing. These states do not allow accurate estimates

of CPA but they are robust in calculating tau as described above. Given that the FAA explicitly prohibits maneuvering an aircraft solely on the basis of TCAS traffic symbology because of the large number of hazards that introduces,⁸ an SAA system will require more than a transponder to avoid WCVs. This additional information may allow accurate predictions of CPA, which could then be compared with a simple distance-based criterion for WCV. The dimensions defining a WCV will include a horizontal radius and vertical range, described colloquially as a “hockey puck.” A reasonable range of distances will be evaluated between the NMAC volume (500 ft radius, 100 ft above and below) and legal SPS requirements (5 nmi and 1000 ft above and below).

III. Studies Evaluating Effects of Well-Clear Threshold

The following section outlines the two analyses comprising this investigation of well-clear metrics and their effects on rates of WCVs.

Analysis 1: Evaluating the effect of well-clear metrics on the rate of WCV occurrence.

In this analysis, the frequency of WCVs between UAS and manned aircraft will be measured as a function of the parameters defining a WCV, including tau, DMOD, miss-distance filters, and horizontal and vertical distances. These measurements will be made when a model of ATC SPS is active and when no separation assurance is provided. This latter case is run to understand the influence of WCV parameters on the applicable rates without the confounding effects of an SPS, not to support a concept in which Class A operations have no SPS. Further analysis will focus on the characteristics of UAS encounters with manned aircraft, including closure rate, relative heading and vertical rate, to study the relative time- and distance separations between aircraft at the boundary of different WCV definitions.

Analysis 2: Understanding the relationship between ATC separation and WCV definition.

In this analysis, we are going to investigate the potential disruptions to ATC that may occur when the distance between aircraft at the instant of a WCV is larger than the ATC separation standards (5nm radius horizontally and 1000ft vertically) as illustrated in Figure 1. When the UAS receives an alert that it will experience a WCV, the UAS pilot may initiate coordination with ATC to maneuver to remain well clear from the intruder or the pilot may take action without coordination. If the UAS is still separated from the other aircraft (i.e. outside the controller’s separation criteria) and the pilot maneuvers without controller coordination, a deviation from the controller’s clearance may occur.

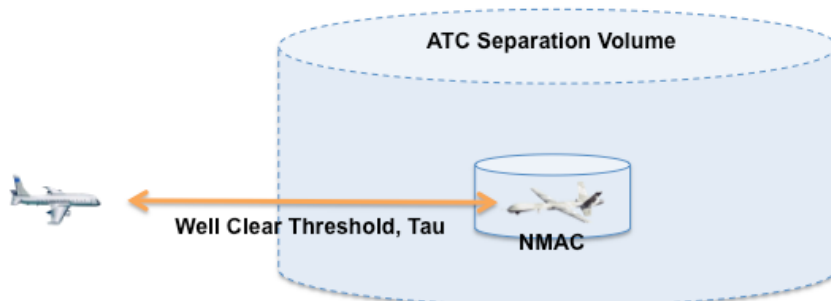


Figure 1: Instance when Well-Clear Threshold is Beyond ATC Separation Volume

Analysis 1 and 2 can inform the relationship between time-based thresholds and distance-based separation volumes (fixed WCV) as it relates to the unmitigated risk of collision. Unmitigated risk of collision is the risk that is incurred crossing a particular relative state given that no avoidance maneuver is undertaken. While not in the scope of this study, future efforts will investigate quantifying the unmitigated risk of well-clear violations given that an intruder passes through that particular relative state and no avoidance maneuver is made. In a future study, the conditional probability that aircraft will experience a WCV will be measured as the ratio of the number of violations to the number of aircraft pairs at specific relative states. It is expected that the number of violations of well clear will decrease as the time or distance boundaries of the relative state increase.

IV. Methodology

A. Simulation Platform

The approach is to use the Airspace Concept Evaluation System (ACES) to investigate the effects of well clear metrics for UAS SAA systems in enroute and transition airspace. ACES, a fast-time agent-based simulation tool, has been used to evaluate various concepts of operations including traffic flow management, separation management, and surface operations through NAS-wide simulations.⁹ ACES provides four-degree-of-freedom (4 DOF) aircraft models and various UAV models such as Global Hawk and Ikhana for the simulation of UAS operations in the NAS.

One of the inputs to ACES is the flight demand set, which consists of all of the flights to be simulated with their aircraft type, their departure and arrival airports, their departure times and their flight plan (waypoints of the route). To simulate current-day traffic operations, a traffic data set is created from data recorded through the Enhanced Traffic Management System (ETMS) for any time and date range. Aircraft Situation Display to Industry (ASDI) data generated from the ETMS can be converted to an ACES flight data set by using the last filed flight plan before takeoff.

The ACES simulation also provides a model of ATC that provides SPS, specifically conflict detection and resolution services. The model is based on the AutoResolver algorithm, which itself is modeled on controllers' methods of separating aircraft, and will be used in this experiment to simulate the ATC SPS.¹⁰ While the AutoResolver heuristically models controllers' methods, this model is not validated, and future work will focus on validation of the AutoResolver against "real-world" data. For simplicity, the Autoresolver algorithm will be referred to as SPS for the remainder of the paper. Although ACES contains algorithms to simulate current-day Traffic Flow Management (TFM) initiatives, the way these initiatives would alter UAS flight plans and departure times in the future is unknown and so no TFM actions were simulated. Not simulating TFM actions should increase the number of aircraft operating in particular areas, so the results presented in this study likely represent a slightly higher than expected rate of encounters.

B. Traffic Scenarios and UAS Missions

For this study, a NAS-wide simulation, which incorporates manned IFR traffic and unmanned aircraft performing atmospheric sampling missions at different altitudes were simulated in ACES. This data set of simulated flights provides actual traffic following their filed flight plans across the NAS, which creates plausible encounters between IFR manned aircraft and UAS. For the actual traffic, Aircraft Situation Display to Industry (ASDI) data for a 24-hour period on Wednesday July 25, 2012 was converted to an ACES flight data set. Approximately 3000 UAS flights following atmospheric sampling missions were included to overlay the background traffic of approximately 50,000 manned flights. The cruise altitudes of the manned flights are given in Figure 2.

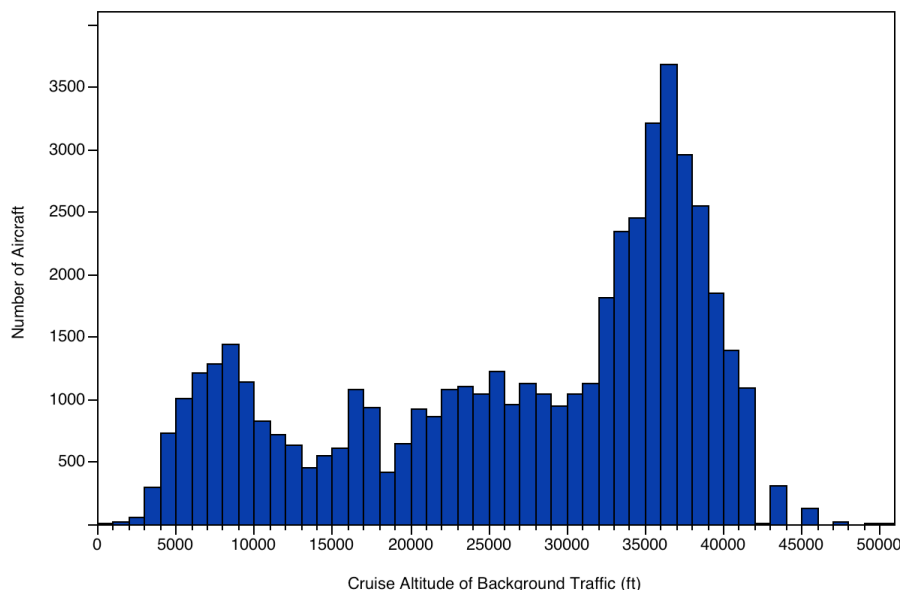


Figure 2: Cruise altitudes of manned background traffic flown on 07/25/2012.

The UAS simulated in this experiment were either of two types: an Ikhana, which represented a "slow" UAS (operating at 170 knots calibrated airspeed) or a Global Hawk, which represented a "fast" UAS (operating at 340 knots). Each UAS was simulated in separate runs to gauge the sensitivity of the WCV to the operational speeds of

the UAS. Each simulation run had the UAS flying a grid pattern representing an atmospheric sampling mission. This flight plan for the atmospheric sampling mission is shown in Figure 3, where the UAS flight plan is shown in magenta and the UAS are depicted as white arrows along the magenta flight plans. The UAS were flown in the simulation at 1000-ft increments between FL300 and FL400 and 5000-ft increments between 15,000 ft and FL300. The cruise altitudes of the background traffic, depicted in Figure 2, span below 15,000 ft to capture potential encounters that occur as the UAS transition to higher cruise altitudes. Flight plans for manned aircraft and UAS begin and end at the boundary of terminal airspace, so terminal area procedures are not simulated. Each UAS flight departs from and arrives at the same airport, with UAS flights operating out of 43 airports spread across the NAS. Multiple flights departed 10 minutes from each other, starting with the flight at 15,000 ft cruise altitude. This corresponds to sets of 14 flights departing within a similar timeframe and a total of six sets of flights in each grid cell of the NAS conducting missions during the peak hours of 5am to 8pm UTC. Figure 4 shows the distribution of number of flights with respect to time and highlights the operational times in which the UAS are flown in the simulation. The total flight hours for the Ikhana and the Global Hawk are 31,713 and 16,347 hours, respectively. The distribution of the duration of the missions that were flown is given in Figure 5 and Figure 6. It is important to interpret the results in the following section as specific to the UAS mission being simulated. Although the atmospheric sampling mission is representative of a possible future UAS mission, the degree to which the metrics presented in this study are well represented by this particular mission is a topic for future research. Aircraft-to-aircraft encounter statistics for the IFR traffic simulated here are not likely to be significantly different when additional UAS missions are introduced, but when this analysis is repeated with VFR traffic the results should be markedly different.



Figure 3: NAS-wide UAS Atmospheric Sampling Mission Profile, UAS tracks in magenta

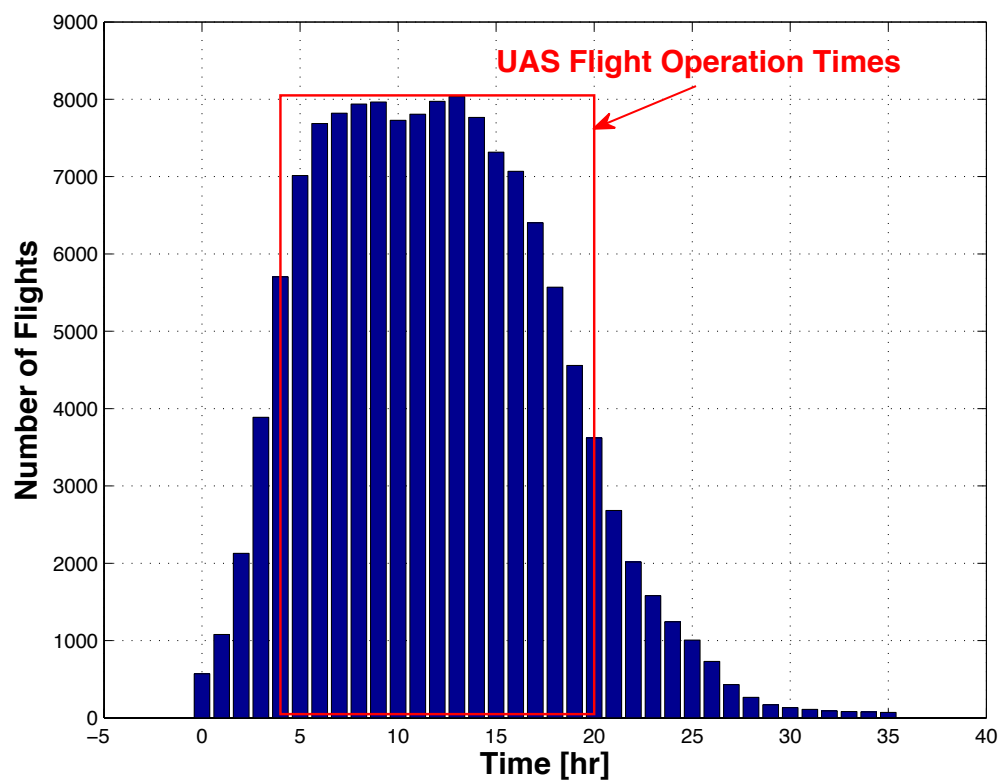


Figure 4: UAS missions are initiated on the peak hours (UTC) of 07/25/2012.

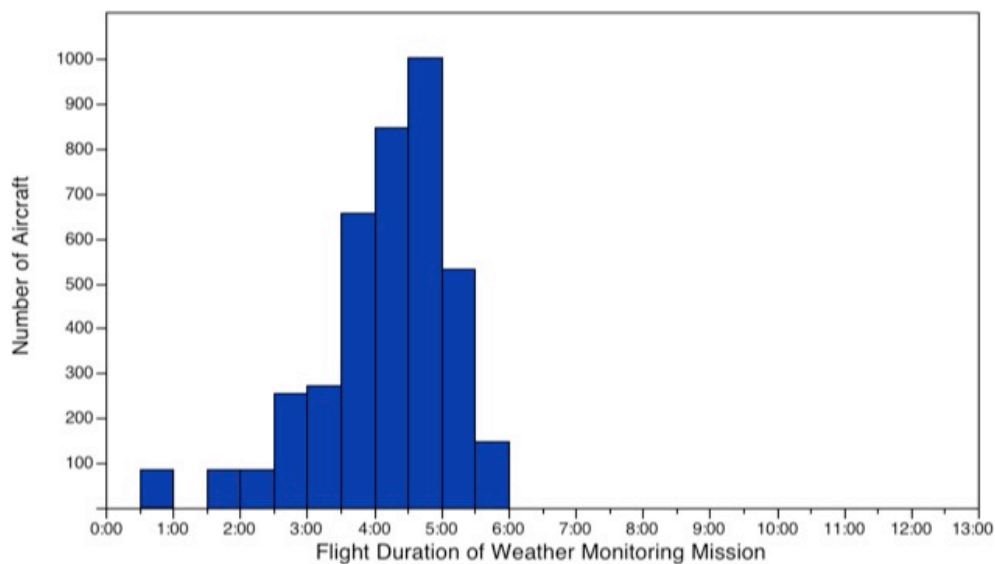


Figure 5: Number of UAS missions flown with respect to mission duration for the Global Hawk.

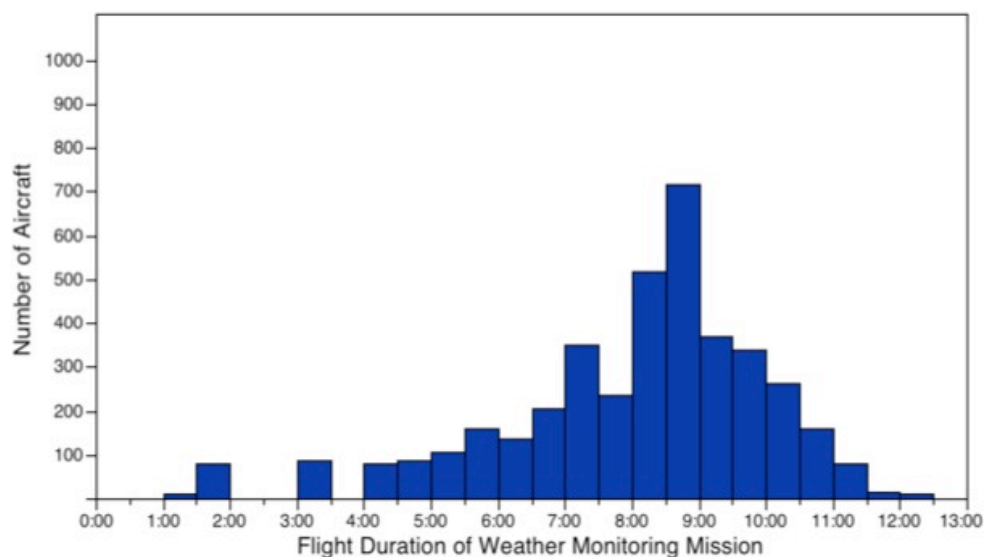


Figure 6: Number of UAS missions flown with respect to mission duration for the Ikhana.

V. Results

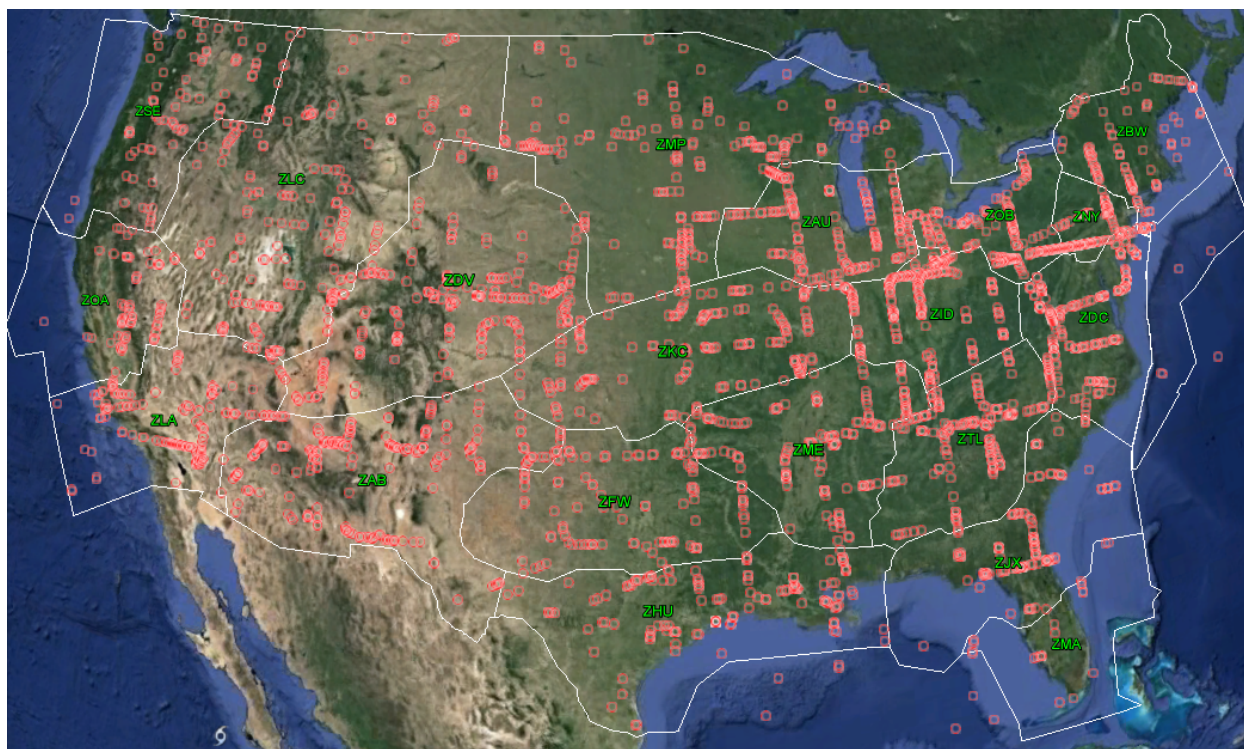


Figure 7: Geographic distribution of loss of ATC separation (5 nmi horizontally and 1000 ft vertically) between Global Hawk and other aircraft.

This study investigates the implications of using different well-clear metrics on the frequency and likelihood of alerting for a well-clear violation. The traffic scenarios used in this study are intended to be representative of IFR current-day operations, and the UAS missions are designed and implemented such as to be representative of feasible mission profiles that are of interest to be flown in the NAS in the near future. Figure 7 and Figure 8

characterize the spatial distribution of encounters simulated in this study, where loss of ATC legal separation (5 nmi horizontally and 1000 ft vertically) is used as a metric to qualify an encounter. Figure 7 depicts the geographical distribution of the coordinates of UAS whose closest point of approach with another aircraft was less than the ATC separation standard. It is evident from Figure 7 that the mission profiles produce a wide spread of conflicts across the NAS. Furthermore, Figure 8 depicts the altitude distribution for the UAS whose closest point of approach to another aircraft was less than the ATC separation standard. Figure 8 produces a distribution that is consistent with the cruise altitudes of the background traffic depicted in Figure 2. Figure 9 depicts the temporal distribution of encounters less than ATC separation. It is evident that the temporal distribution corresponds to the peak hours of background traffic detailed in Figure 4. The results in Figure 7, Figure 8, and Figure 9 demonstrate that the simulation creates a breadth of encounters in terms of quantity and location. The encounter characterization, depicted in Figure 7, Figure 8, and Figure 9, produced similar results for the Ikhana aircraft. For brevity the Ikhana encounter characterization figures are not included in this report.

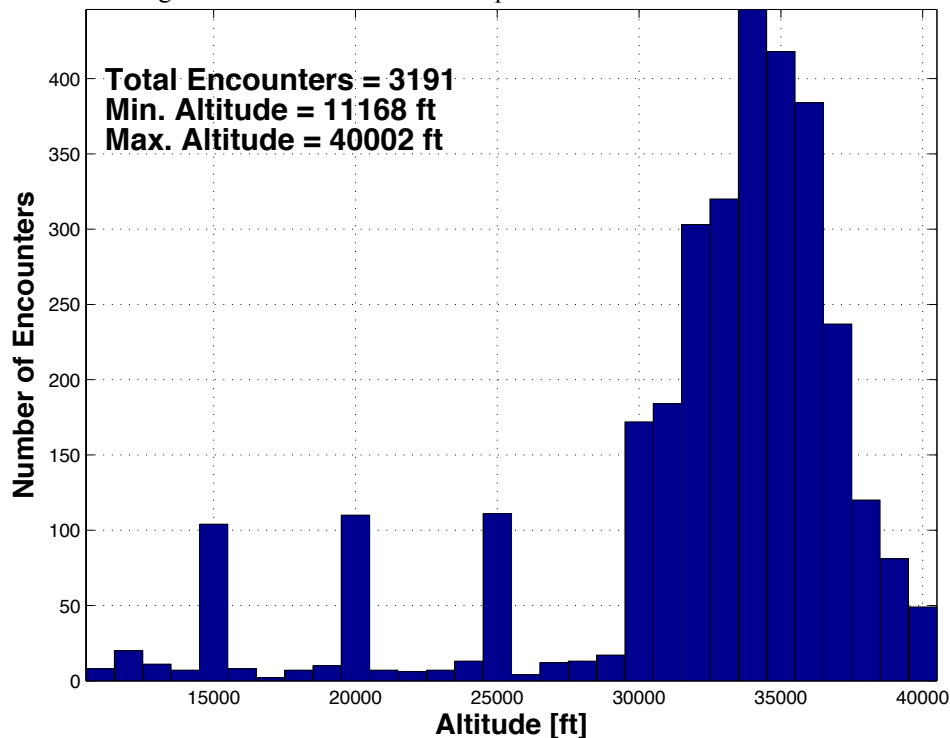


Figure 8: Flight altitude distribution of loss of ATC separation (5 nmi horizontally and 1000 ft vertically) between Global Hawk and other aircraft.

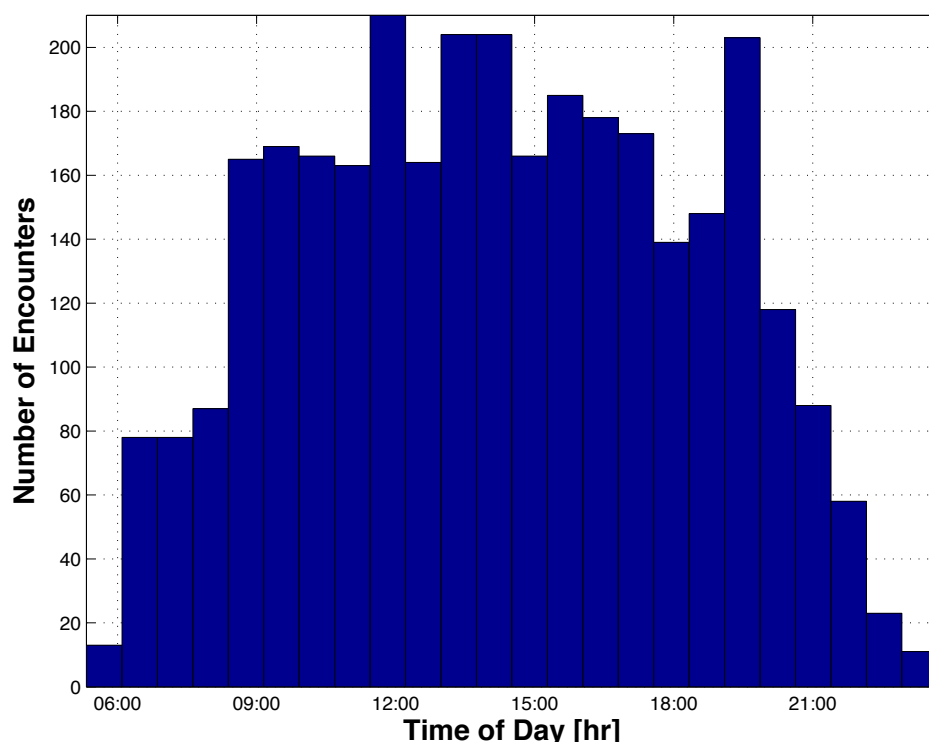


Figure 9: Flight time of day (UTC) distribution of loss of ATC separation (5 nmi horizontally and 1000 ft vertically) between Global Hawk and other aircraft.

A. Analysis 1:

Analysis 1 is evaluating the effect of well-clear metrics on the rate of WCV occurrence. For this analysis the range tau (see eq. 1), modified range tau (see eq. 3), and modified range tau with DMOD horizontal (1.1 nmi) and vertical (700 ft) miss-distance filters were calculated for every pair of UAS and manned aircraft. To demonstrate the sensitivity of the miss distance filtering, an arbitrary filter volume (denoted as VOL in plots) is given as 3.5 nmi horizontal and 1000 ft vertical miss distances. This analysis also contrasts the impact of having the rate of encounters with and without SPS. In addition, distance-based metrics are calculated for every pair of aircraft whose displacements violate the ATC legal separation standard (5 nmi horizontally and 1000 ft vertically) and a separation volume based on DMOD parameters (1.1 nmi horizontally and 700 ft vertically). Figure 10 shows a plot of the rate that Global Hawk UAS encountered other aircraft as a function of the pair's minimum tau. Figure 10 also demonstrates the rate of encounters of pairs of aircraft that violate the distance-based separation metric, displayed as horizontal lines (ATC Separation Violation and DMOD Separation Violation). Furthermore, Figure 11 demonstrates the rate in which the Ikhana encountered other aircraft. One observation that can be drawn from Figure 10 and Figure 11 is that, while there is strong correlation between range tau and modified tau metrics, both metrics alert at a much higher rate than the modified tau with the miss distance filters. Comparing the modified tau with DMOD miss distance filter versus that with the VOL miss-distance filter, it is evident that the size of the filter is strongly indicative of the encounter rate that will be observed for larger values of tau. For instance, if using the modified tau with DMOD miss-distance filtering, the encounter rate for a distance-based DMOD criteria (1 encounter for every 10 hours) would serve as an upper bound of the encounter rate for a given tau. Furthermore, the encounter rate for UAS has minimal sensitivity to operational speed differences in the mission conducted with the faster UAS (Global Hawk) and the slower UAS (Ikhana). Figure 10 and Figure 11 also contrast the differences between the time-based metrics and the distance-based metrics. For instance, the simulation yielded UAS encountering other aircraft within the ATC separation volume at a rate of 0.25 encounters per flight hour, which corresponds to the rate of less than approximately 75-80 seconds for range tau and modified tau.

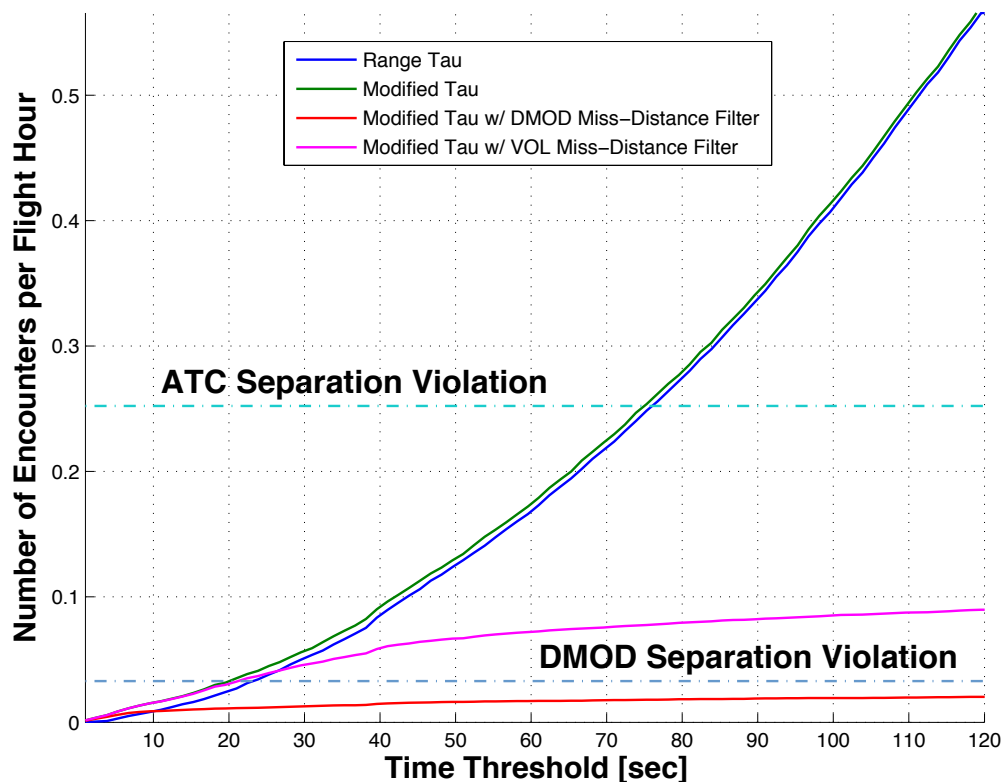


Figure 10. Relationship between minimum tau between aircraft pairs and the rate of encounter per UAS flight hour for the Global Hawk UAS.

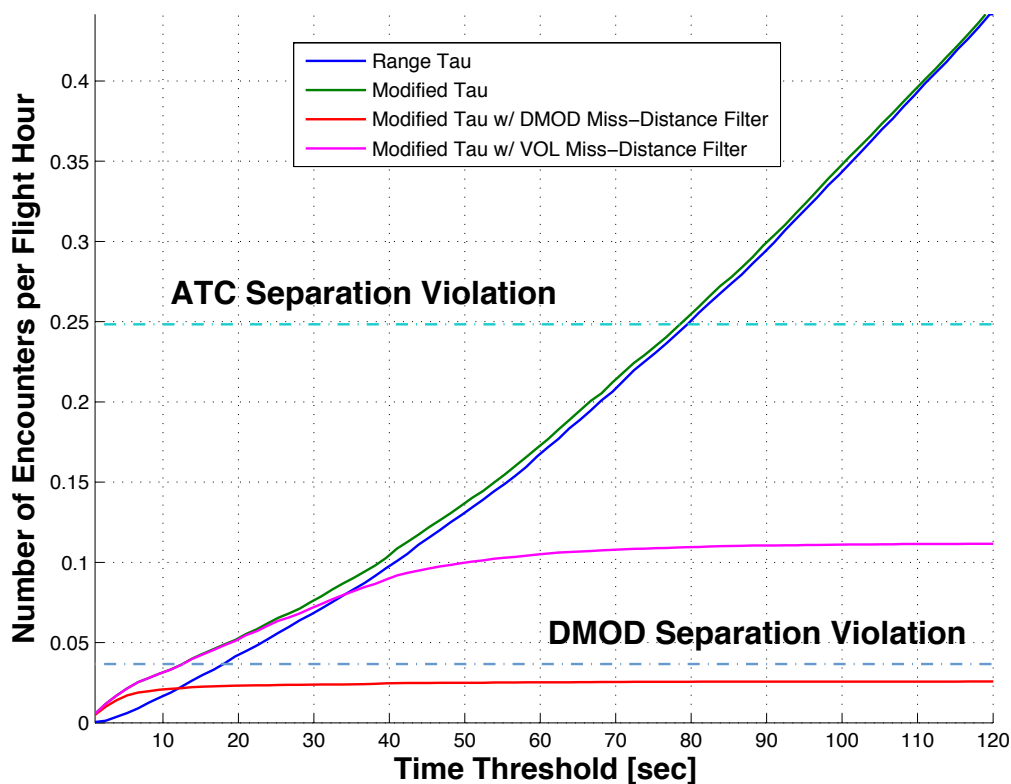


Figure 11: Relationship between minimum tau between aircraft pairs and the rate of encounter per UAS flight hour for the Ikhana UAS

Figure 12, depicts the effect of an SPS on the encounter rate or (conversely) the tau corresponding to a given encounter rate. As depicted in Figure 12, for an encounter rate of 0.1 per hour, the modified tau increases from ~40s to over 70s. Further simulations and human-in-the-loop studies with a variety of UAS missions will determine what the acceptable rate of encounters would be for UAS missions when SPS is provided. If further simulations show that UAS encountering other aircraft at a rate of 0.1 per hour (which corresponds to a modified 70-second tau) is a feasible upper bound, then any reasonable definition of a WCV (i.e. $\tau < 70$ s) using range tau or modified tau should not cause the SAA system to alert the pilot to a potential WCV. However, the actual minimum tau between pairs of aircraft does not indicate whether a predicted minimum would be within the definition of a WCV and would cause a pilot alert before the controller acted to resolve the potential WCV.

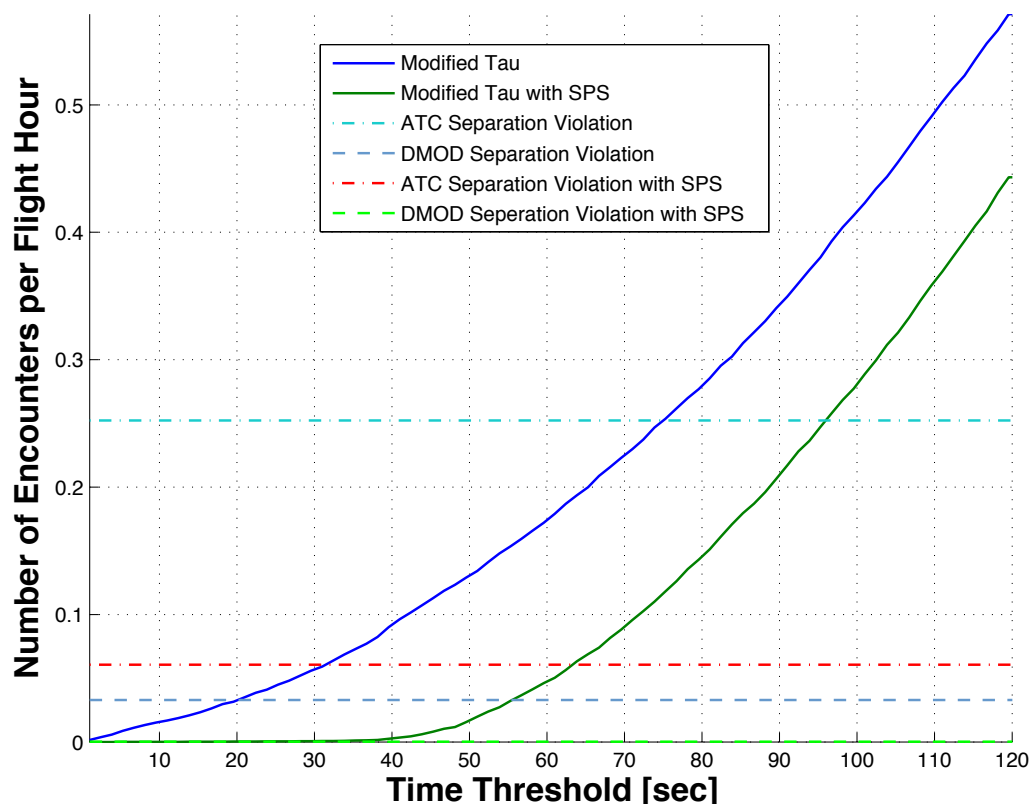


Figure 12: Relationship between minimum range tau between aircraft pairs and the rate of encounter per UAS flight hour for the Global Hawk UAS with and without SPS.

B. Analysis 2:

Analysis 2 is aimed at understanding the relationship between ATC separation and WCV definition, and the potential disruption to ATC that would be caused by alerting from the SAA system. In this analysis, it is assumed that alerts prior to loss of ATC separation could potentially disrupt ATC services. The time-based tau thresholds are varied and the number of alerts occurring prior to loss of ATC separation is compared. Figure 13 depicts the percentage of alerts issued when a UAS conflict pair encroaches on a specified tau threshold, but the range between the aircraft is greater than the ATC separation standard. It is evident from Figure 12 that, when the range tau and modified tau alerting threshold was set to 60 seconds, 70-80% of the total alerts were for aircraft pairs that were greater than 5 nmi horizontally and 1000 ft vertically. Although the proportion of alerts prior to violation of the ATC separation standard is significant, it should be noted that the result from Figure 10 and Figure 11 demonstrates that the alerts would occur once every 5-6 hours. In these instances, the WCV is outside the controller's separation criteria and the pilot may try to maneuver before the controller issues a separation clearance to resolve the WCV. This action could cause a significant disruption to the controller's operations.

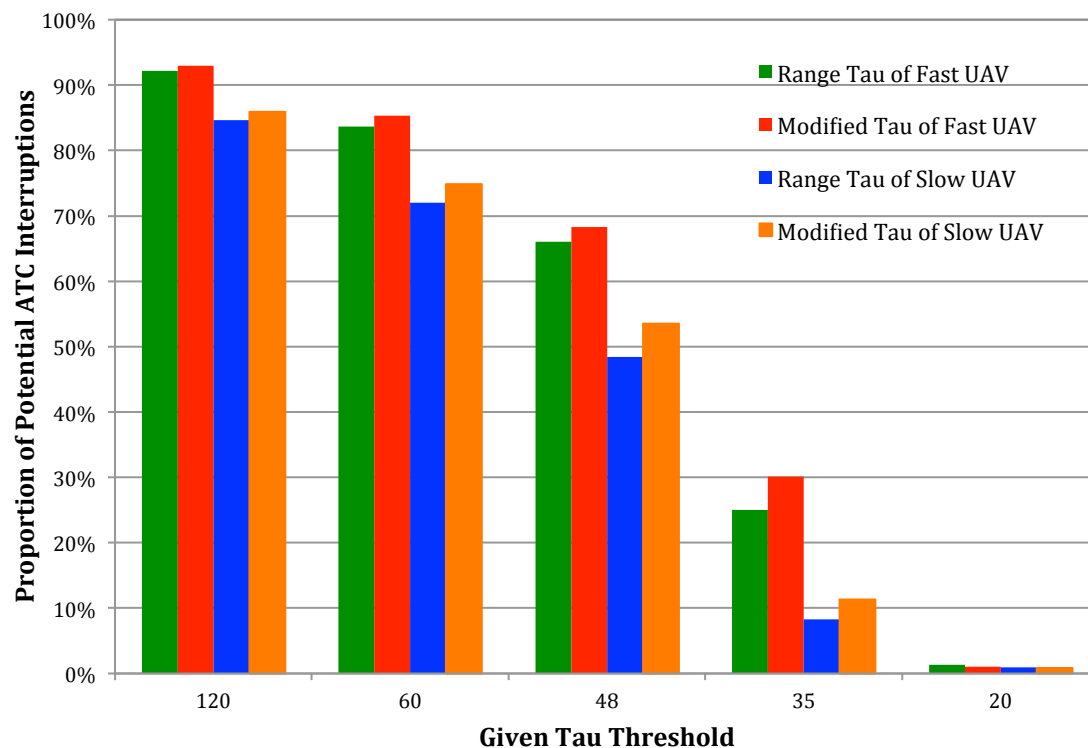


Figure 13: Proportion of alerts issued by a UAS for encounters with another aircraft outside of the ATC separation standard with respect to a given tau threshold.

This analysis further investigates the relationship between the time-based thresholds and distance-based separation volumes in the definition of well clear. Figure 14-Figure 17 show the distribution of horizontal and vertical separation that is calculated at a range tau threshold of 60 seconds and 20 seconds, respectively. In Figure 14 and Figure 15, it is evident that a tau threshold of 60 seconds produces a large spread of horizontal and vertical separation. Recalling the results from Figure 12, it is evident that approximately 80% of the alerts that are issued at this threshold lie outside of the ATC legal separation standard. Furthermore, Figure 16 and Figure 17 demonstrate that the average separation distances decrease as the tau threshold decreases. This trend is consistent for the modified tau as well.

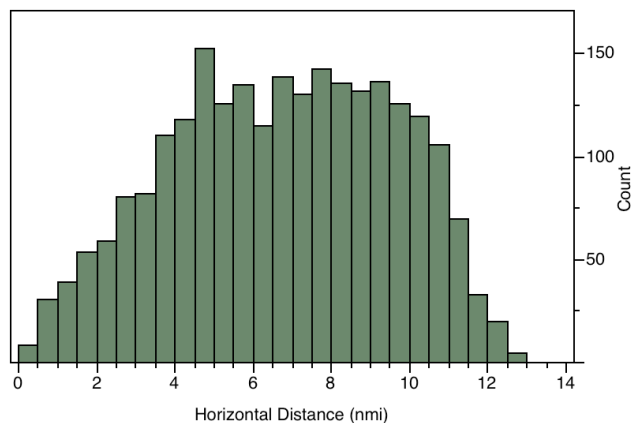


Figure 14: Distribution of horizontal separation between Global Hawk and other aircraft for 60 seconds range tau.

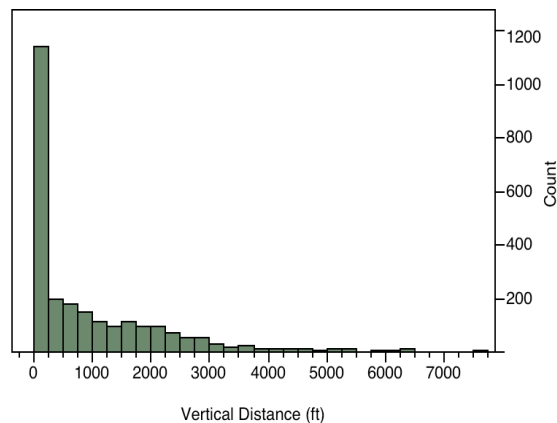


Figure 15: Distribution of vertical separation between Global Hawk and other aircraft for 60 seconds range tau.

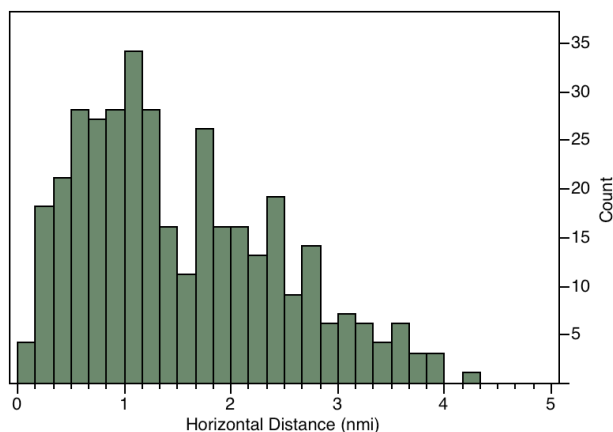


Figure 16: Distribution of horizontal separation between Global Hawk and other aircraft for 20 seconds range tau.

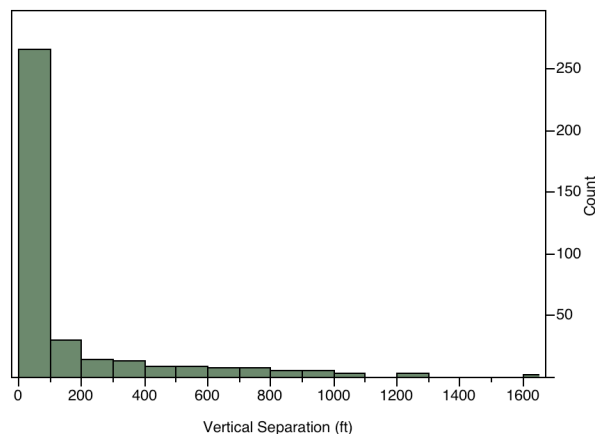


Figure 17: Distribution of vertical separation between Global Hawk and other aircraft for 20 seconds range tau.

VI. Concluding Remarks

A UAS SAA system will replace an onboard pilots' ability to see and avoid other traffic in a manner that preserves the safety of the airspace and the efficiency of the air traffic system. An SAA system must adhere to a quantitative definition of "well clear" in order to perform the self-separation function. In this study, several potential metrics for well clear are analyzed using a fast-time NAS-wide simulation tool to understand the effects these definitions have on the safety and efficiency of the ATC system in enroute and transition airspace. This study addresses trade-offs among the well-clear measures and evaluates how frequently an SAA system might be expected to alert to a possible well-clear violation. The results indicate that the encounter rates for range tau and modified tau are similar, and both are on the order of one encounter under a tau of 60 seconds for every six UAS flight hours. A significantly lower encounter rate occurs when miss-distance filtering is applied to the modified tau calculation, only one encounter every forty UAS flight hours. The miss distance filtering is a hybrid temporal and spatial metric, where the filter volume acts as an upper bound on the encounter rate and results in lower alerting frequency of alerting than the purely time-based metrics. Furthermore, the results contrast encounter rates of distance-based thresholds to equivalent time-based thresholds. When ATC is providing SPS, the results indicate that encounters

under a tau of 30 seconds are virtually non-existent. For a given operationally acceptable encounter rate, the results where SPS is provided imply that a tau-based upper bound could be established such that selection of a tau threshold less than that upper bound would result in minimal alerting of the SAA system in high-altitude airspace. Further human-in-the-loop studies involving air traffic controllers and UAS pilots would need to be conducted to establish the operationally acceptable encounter rates. A metric related to the acceptability of nuisance alerts is the range between aircraft at which a well-clear violation occurs: for a 60-second tau approximately 75% of all violations would occur outside the controller separation standard of 5 nmi. This demonstrates that using range tau or modified tau metrics without horizontal and vertical miss-distance filtering are likely to produce too many “nuisance” alerts. This preliminary study should inform selection of an appropriate definition of well clear for UAS SAA systems and motivate further research on what it means for aircraft to be well clear.

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